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In-Flight Validation of

Small Deep Space Transponder (SDST)

DS1 Technology Validation Symposium

February 8-9, 2000

Pasadena, CA

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Outline

- Introduction and Acknowledgment
- SDST Overview
- Flight Validation Process
- Detailed Results
- Summary and Conclusions

Acknowledgments

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- **SDST Development Team**
- **DS1 Telecom Team**
- **DS1 Flight and Mission Suport Team**

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Introduction to SDST

- Developed by Motorola SSG under funding from a JPL multimission consortium
  - intended as a replacement for the Cassini Deep Space Transponders (DST)
  - Integrate function of command detector unit and telemetry modulation units
  - First transponder with integrated Ka-band functions

- Total Development cost of $10.4 million dollars
- Total Development time less than 3 years

	DS1	Mars Pathfinder (equivalent function)
Mass	3 kg	TMU: 0.435 kg DST: 4.000 kg CDU: 0.365 kg
Power	12.9 W	TMU: 1.4 W DST+CDU: 13.1 W

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Small Deep Space Transponder

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Capabilities

- X-band receiver/ down-converter capable of carrier tracking at or below -156 dBm.
- Command detector unit function
- Telemetry Modulation function
- X- and Ka-band exciters
- Beacon Mode Operation
- Coherent and non-coherent operation choice
- X- and Ka-band ranging
- Differential One-Way Ranging (DOR) for both X- and Ka-bands
- C&DH communication via 1553
- Data interface via RS422
- External ports for temperature sensors
- External port for analog signal

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SDST KEY TECHNICAL OBJECTIVES

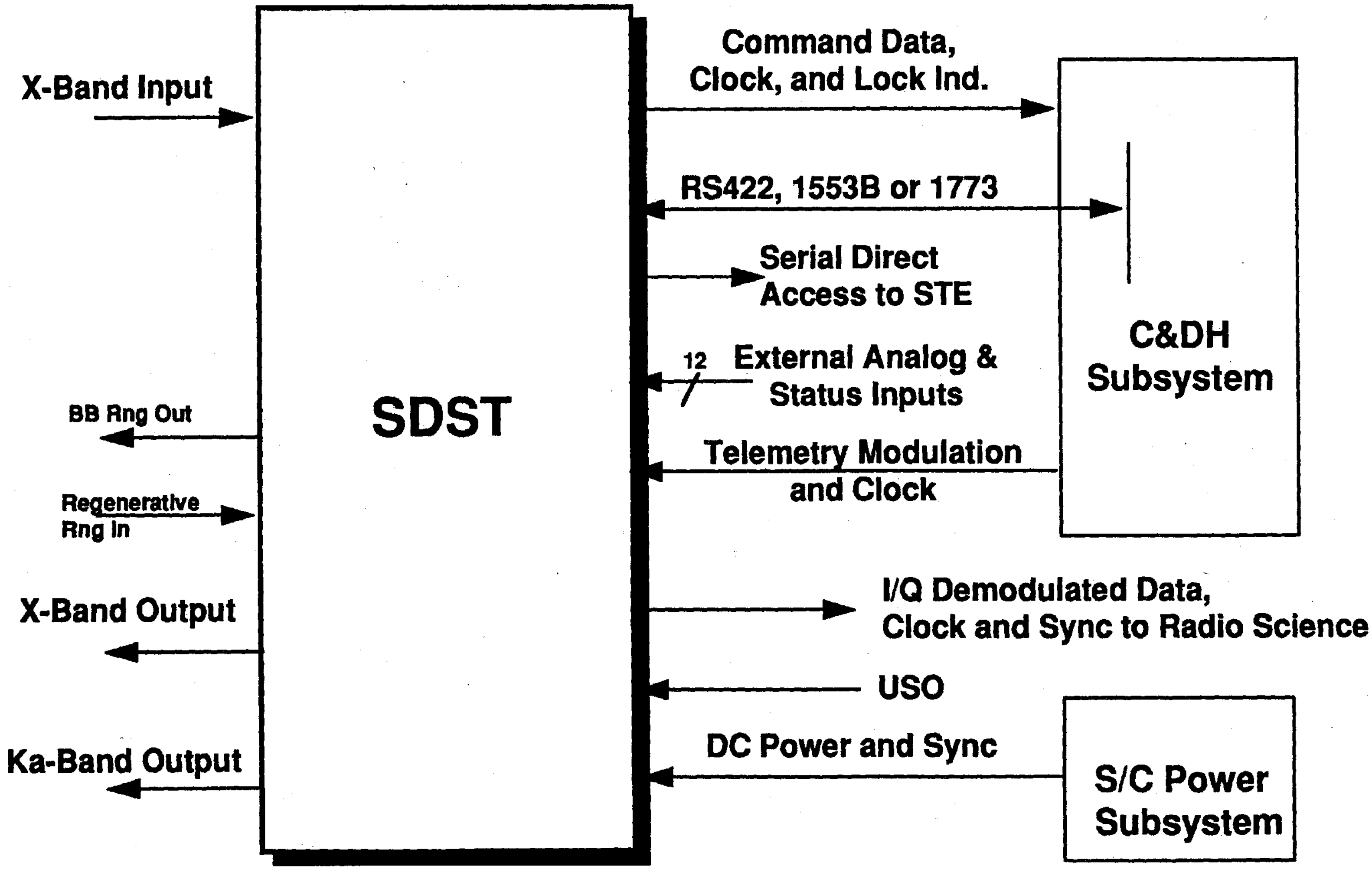
OBJECTIVES

- Combine X/Ka-band transponder, command detector unit (CDU), and telemetry modulation unit (TMU) into a single small assembly.
- Add lower-level definition to 19 page high-level procurement specification.
- Balance new technology use with risk:
  - New 70,000 gate rad.-hard CMOS ASIC
  - New MOSAIC 3 Radio Frequency Integrated Circuit (RFIC)
  - Three new RF multi-chip modules using low- temperature co-fired ceramic substrates
  - Use custom microwave monolithic integrated circuits developed specifically for deep-space transponders
  - Reuse the "best" technology in the Cassini transponder

PERFORMANCE

- X-band receiver, CDU, TMU, X-band exciter and Ka-band exciter combined into single 6.95 in x 5.5 in x 4.48 in package with 3.0 kg mass.
- Detailed 71 page MARS 2001 / SIRTF specification completed
- Achieved a good compromise:
  - ASIC required no iterations
  - RFIC required one minor iteration (metal layer only)
  - No MCM changes for DS1. Minor changes for MARS 2001/SIRTF flight units.
  - Used Pacific Monolithics phase modulator MMIC developed on JPL Small Business Innovative Research grant and LNA MMIC developed on Motorola IRAD.
  - DRO, TCXO, 5 pole ceramic filter, and preselector filter designs reused

SDST HIGH LEVEL INTERFACES



SDST RF TECHNOLOGY KEY FEATURES

- New technology greatly reduces size
  - 3 RF Multi-chip modules
  - Downconverter RFIC
- RF Multichip Modules
  - Moderate complexity to minimize risk
  - Typically consist of 4 MMICS and their active bias circuitry. No tuning.
  - Use 13 layer, low-temperature co-fired ceramic substrates. Hermetically sealed.
  - Small size: 1.4" W x 2.2" L
  - Waveguide beyond cutoff provides high internal isolation without shielding
- Downconverter RFIC
  - Motorola MOSAIC 3 process
  - Radiation hardness > 100 kRad (Si)
  - Single monolithic die: 88 mils x 88 mils
  - S/L-band input , dual conv. to 10 MHz IF
  - 80 dB conversion gain
  - 90 dB AGC range minimum
  - Internal 1st LO oscillator
  - Few external components required
  - Also used in TDRSS IV transponder
- Common sampling phase-detector LO synthesis approach
  - Uses high Q, dielectric or ceramic resonator VCOs
  - Extremely low phase noise, Allan Dev.
  - Worst case analyzed for acquisition and loop stability
- Proprietary low phase-noise receiver TCVCXO and exciter AUXOSC
  - TCXO < ± 3 ppm, -20°C to + 50°C
  - AUXOSC phase noise < -20 dBc/Hz @ 1 Hz offset referred to X-exciter output
- 97A13L custom Motorola LNA MMIC has nearly same power/noise figure performance as Cassini discrete LNA design. 1 dB NF.
- S93031 custom Pacific Monolithics phase modulator MMIC replaces Cassini discrete design
- Small integrated X/Ka band X4 multiplier / filter / isolator assembly

SDST DIGITAL TECHNOLOGY KEY FEATURES

- Digital Signal Processing Approach
  - 1 ASIC to minimize risk, recurring cost
  - Turnaround ratio set in RF modules
  - Firmware definable: DSN, GN, SGLS
  - ASIC performs high-speed DSP
  - Firmware performs lower-speed DSP
  - Allows fixes to algorithms without cost / schedule impact of ASIC turn
  - Easily adapts to new requirements
- Digital Signal Processing Functions
  - Coherent down-conversion to baseband
  - Carrier AGC loop
  - Carrier lock detector
  - Carrier tracking loop filter
  - Command detector: DSN, GN, ESA, SGLS
  - Ranging detector, Ranging AGC
  - 4 TLM convolutional encoders
  - Bi-phase TLM encoder
  - TLM Subcarrier NCO
  - TLM and Ranging mod index selection
  - Independent X/Ka exciter TLM functions
  - Transponder control / engineering TLM
- 70,000 gate CMOS ASIC
  - UTMC UTE-R, 1.2 micron process
  - Radiation hardness > 100 kRad (Si)
  - Internal RAM
  - Low power < 0.5 Watt
- RISC Microprocessor
- External TLM digitizing
  - 4 temperature TLMs
  - 4 status TLMs
  - 4 analog TLMs
  - Great for S/C RFS telemetry!
- Interfaces
  - MIL-STD-1553B
  - MIL-STD-1773
  - RS-422 with MIL-STD-1553 protocol
- Direct Access Interface
  - RS-422 serial, Motorola protocol
  - Mode control and engineering TLM
  - Provides independent RFS monitoring during S/C integration using SDST STE in data logging mode.

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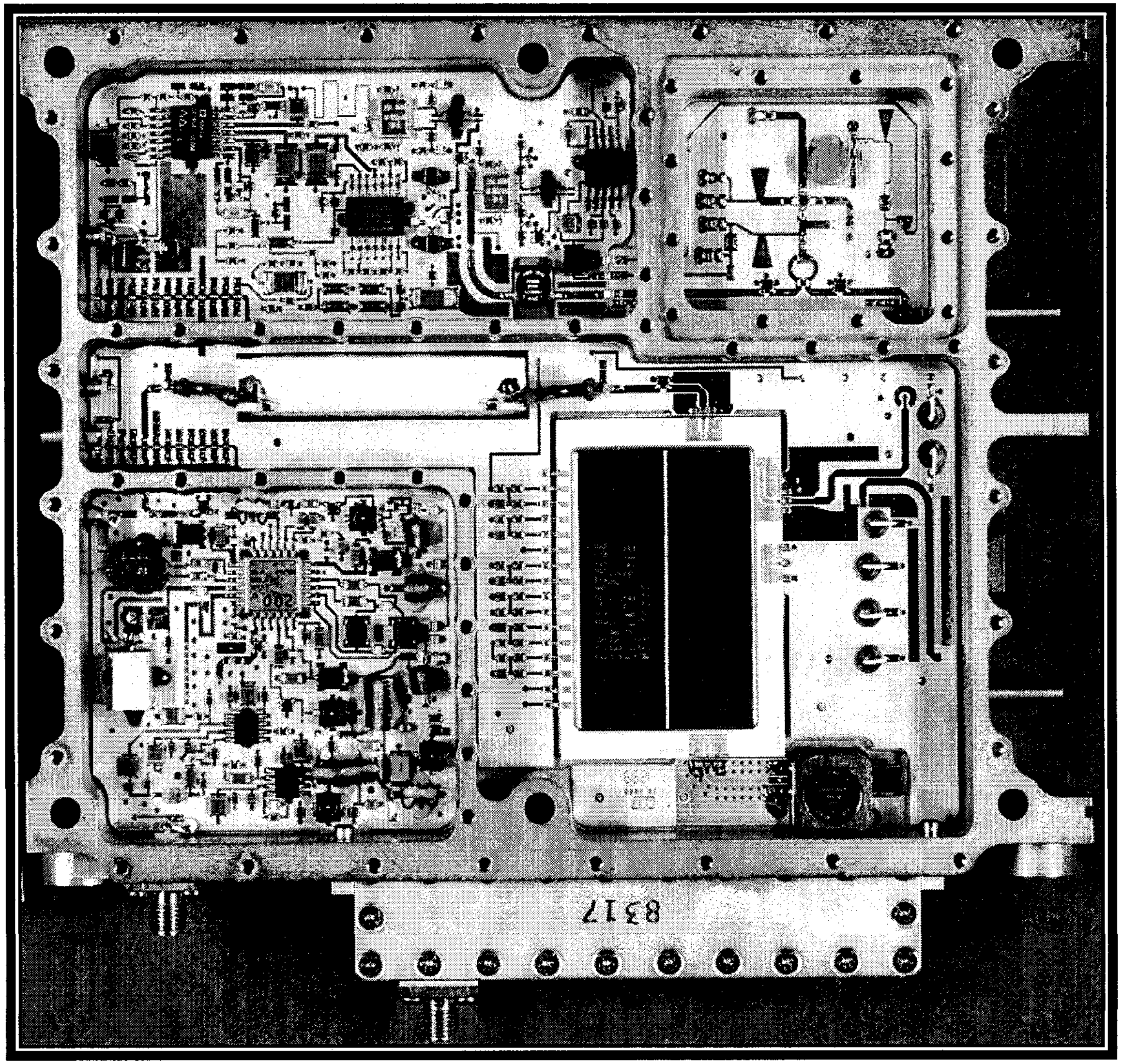
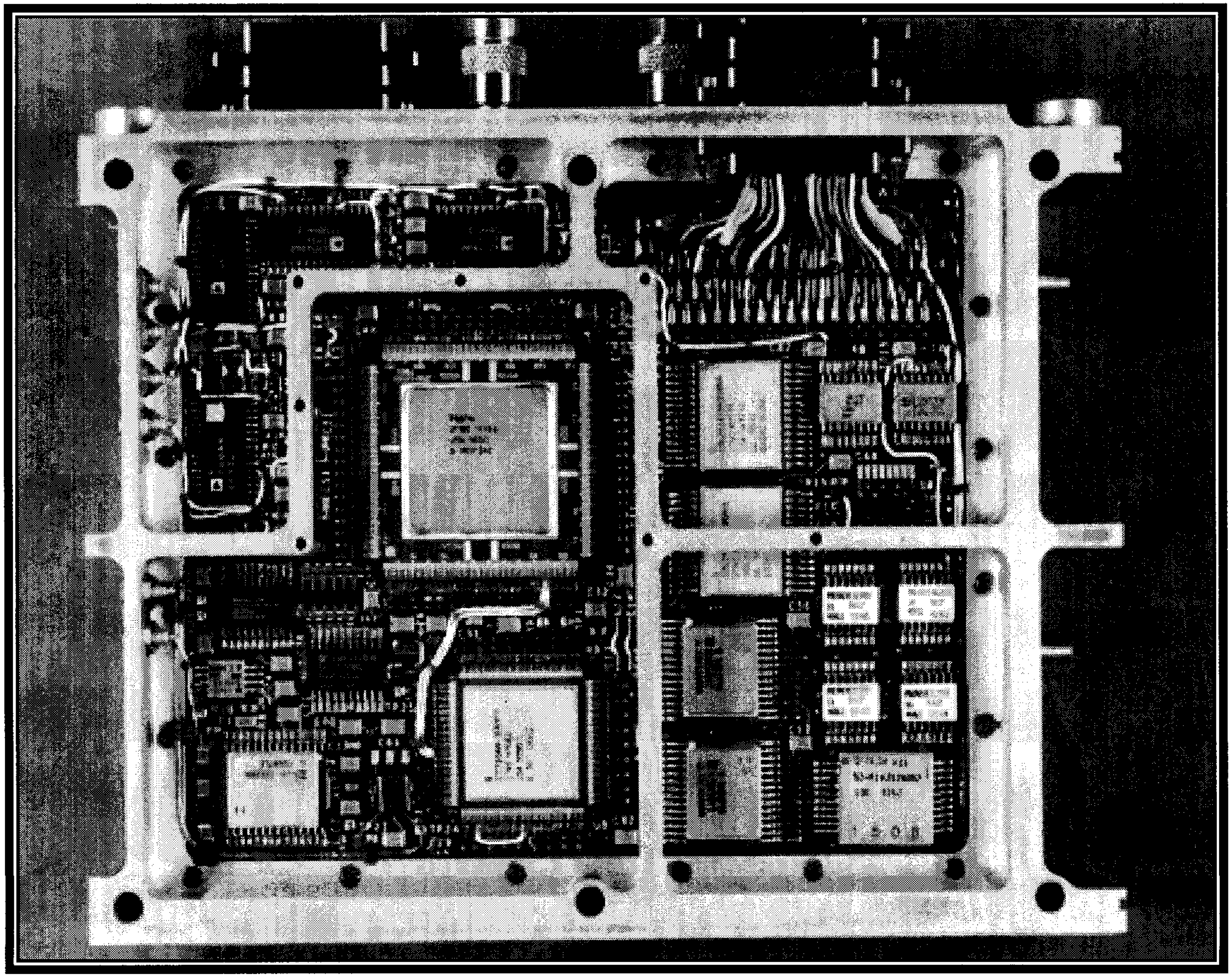
SDST RF PACKAGING



SDST DPM PACKAGING



Technology Validation Approach

- **Ground Acceptance and Functional Tests**
  - Verification of requirements
  - Characterization of key performance parameters
- **DSN Compatibility Tests**
  - Validate design capability for uplink, downlink, and radiometrics
  - Validate compatibility with DSN
- **Flight Validations**
  - Demonstrate performance and reliability
  - Validate functions in actual operating environment
  - Conduct performance measurements not otherwise possible on the ground

InFlight Validation Objectives

- Uplink Functions
  - Uplink carrier receiver acquisition
  - Command data rate and command threshold
  - Carrier tracking and uplink power measurements
- Downlink Functions
  - Verification of telemetry encoding and carrier modulation
  - Verification of transition between two-way coherent and one-way modes
  - Validation of the phase modulator performance model
  - Validation of the Ka-band exciter technology and its associated performance characteristics
  - Validation of beacon tone generation
- Radio Metrics Functions
  - Measurement of frequency stability of the DS1 auxiliary oscillator under inflight temperature condition.
  - Verification of coherent carrier tracking performance
  - Verification of the X/Ka-band relative carrier tracking performance
  - Verification of the X/Ka-band ranging functions

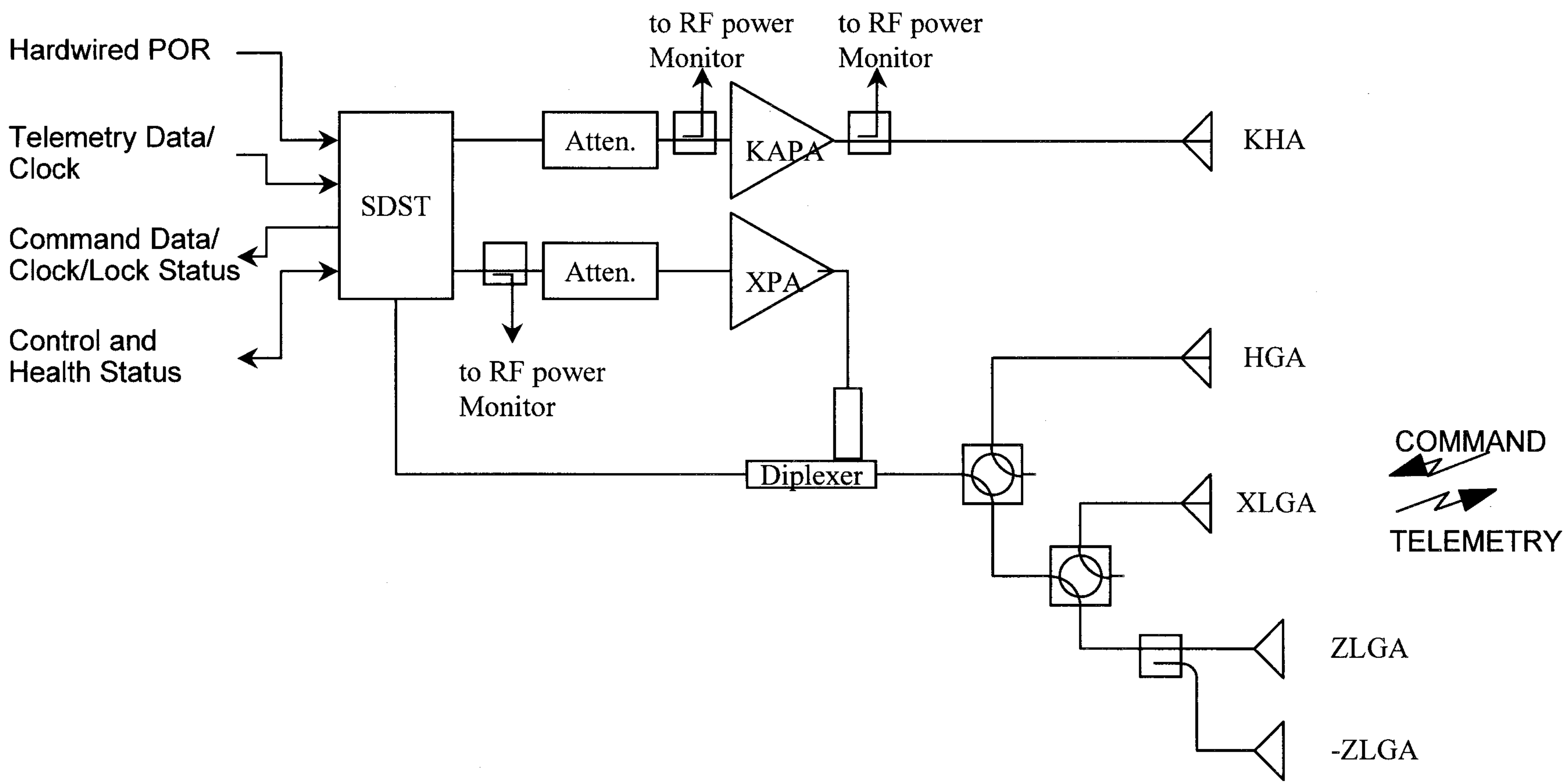
Additional Ka-band Validation Objectives

- **Validate DSN Readiness to Support Ka-band**
  - Demonstrated dual-band (X/Ka) end-to-end telemetry flow from spacecraft to DS1-MSA
  - Demonstrated capability to generate necessary station predicts for Ka-band tracking
  - Demonstrated station capability to perform radio metric tracking on Ka-band downlink (Doppler and ranging)
  - Verified X/Ka band Radio metrics performance
- **Validate Ground antenna pointing capability**
- **Verify link performance projection**
- **Measurement of Ka-band downlink signal detection threshold**
- **Ka-band Antenna Pointing and Gravity Compensation at 70 m**

Validation Process

Objectives	Prelaunch	Inflight Checkout	Tests
Receiver best lock frequency	Measure	Validate	Routine Ops
Signal Acquisition Range and Rate	Measure	Validate	Routine Ops
Self/false lock characterization	Measure	Validate	Routine Ops
Uplink Command reception	Measure	Validate	Routine Ops
Uplink Power Measurements	Characterize	Validate	Routine Ops
Telemetry encoding and modulation	Test	Validate	Routine Opts, XTLM
Noncoherent mode Operation	Test	Validate	Routine Ops
Phase modulator performance	Characterize	Validate	Routine Ops Xrange
Noncoherent carrier frequency stability	Test	Measure	Xstable
Coherent Doppler Tracking Performance	Test	Validate	Routine Ops
Ranging functional verification	Test	Validate	Xrange KRange
Beacon Mode (a separate experiment)	Test	Validate	Xtone
Analog Engineering Telemetry Sampling	Test	Validate	Routine Ops

DS1 Telecommunications Subsystem



Separate X-band and Ka-band downlink antenna

Ka-band SSPA (KAPA) provided by Lockheed Martin through NM IPDT

Flight Validation Results - Uplink

- Demonstrated uplink carrier receiver acquisition
  - Problem with DS1 implementation resulted in large (+/- 20 kHz) change in receiver best lock frequency over temperature
  - Sweep strategy (rate and range) determined from ground test (DSN Compatibility Tests) results
  - No failed acquisition in flight due to transponder
- Demonstrated command data rate and command threshold
  - All commandable data rate (except 31.25 bps) demonstrated in space
  - No command is lost when uplink is tuned using recommended command threshold
- Carrier tracking and uplink power measurements
  - Uplink residuals compiled showed good agreement with predicts

Flight Validation Results - Downlink

- Demonstrated Telemetry encoding and carrier modulation
  - Demonstrated all 18 X-band data rates and 14/18 data rates at Ka-band
  - Demonstrated both (7, 1/2) and (15, 1/6) convolutional coding
- Demonstrated Transition between two-way coherent, one-way and two-way noncoherent modes
- Validated Phase modulator performance model
  - Nonlinearity of phase modulator resulted in large intermod losses at high ranging/telemetry modulation indices
  - Measurements of carrier suppresssion due to telemetry and ranging confirmed model from ground-based test results
- Successfully generated all 4 Beacon tones and detected beacon downlink on the ground

Flight Validation Results - Radio Metrics

- Measured frequency stability of the DS1 auxiliary oscillator under inflight temperature condition.
- Verified of coherent carrier tracking performance
  - Demonstrated X- and Ka-band Doppler tracking data delivery
  - Measured in flight X- and Ka-band two-way Allan Deviation
- Verification of the X/Ka-band ranging functions
  - Demonstrated X- and Ka-band ranging capabilities
  - Measured ranging power correlates well with predicts (typically within a few dBs)

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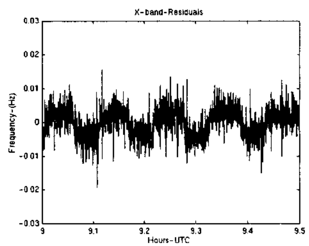
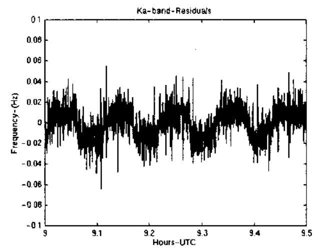
Flight Validation Results - Cohernet Tracking

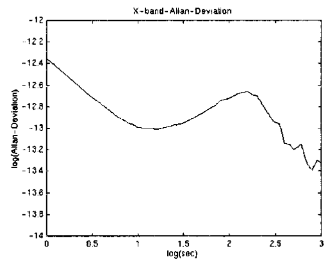
- Frequency residuals are highly correlated between X- and Ka-band
- Spacecraft deadband is the dominant source of frequency residuals
- X-Ka band residuals still shows effect of spacecraft deadbanding because of offset in antenna positions



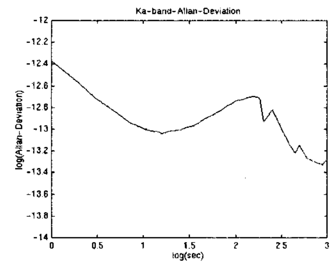
X-band



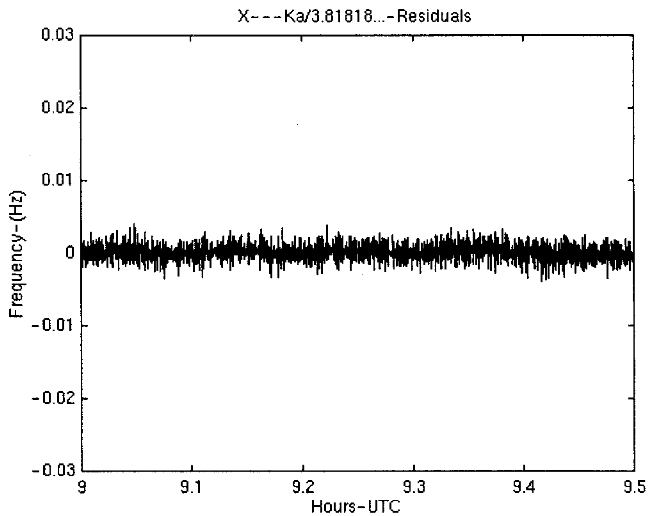
Ka-band



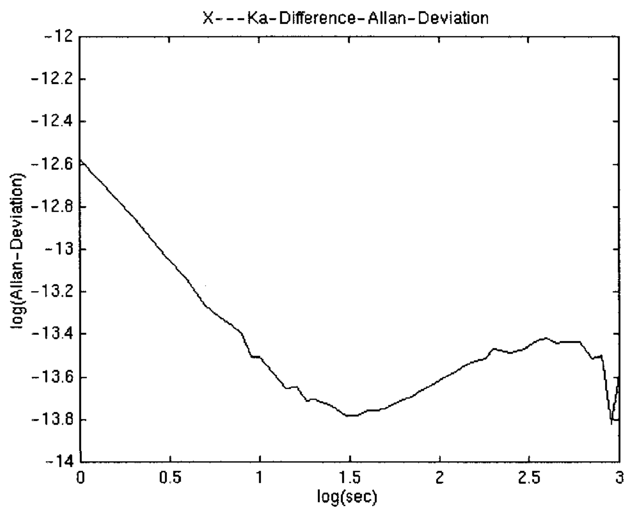
X-band



Ka-band



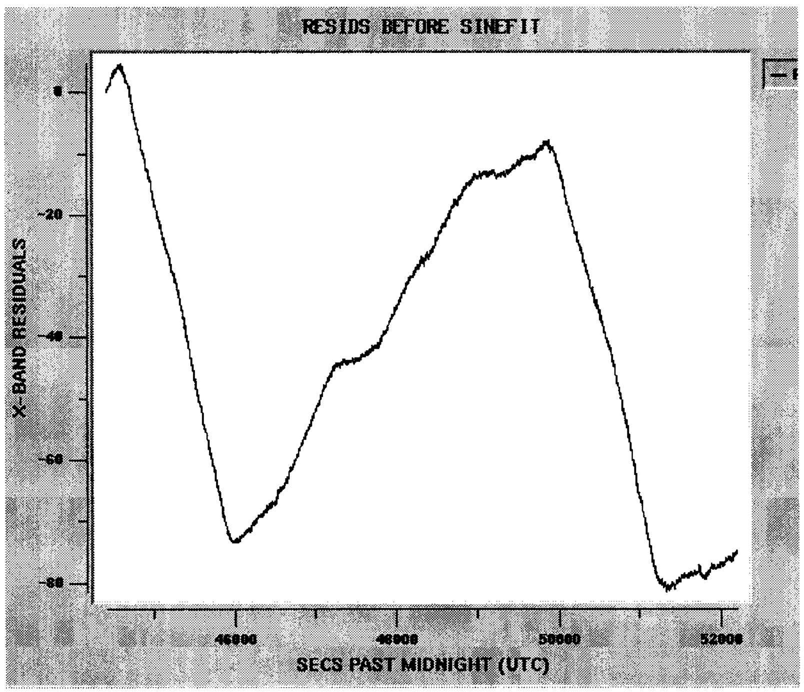
Frequency Residuals of X-Ka Band Residuals

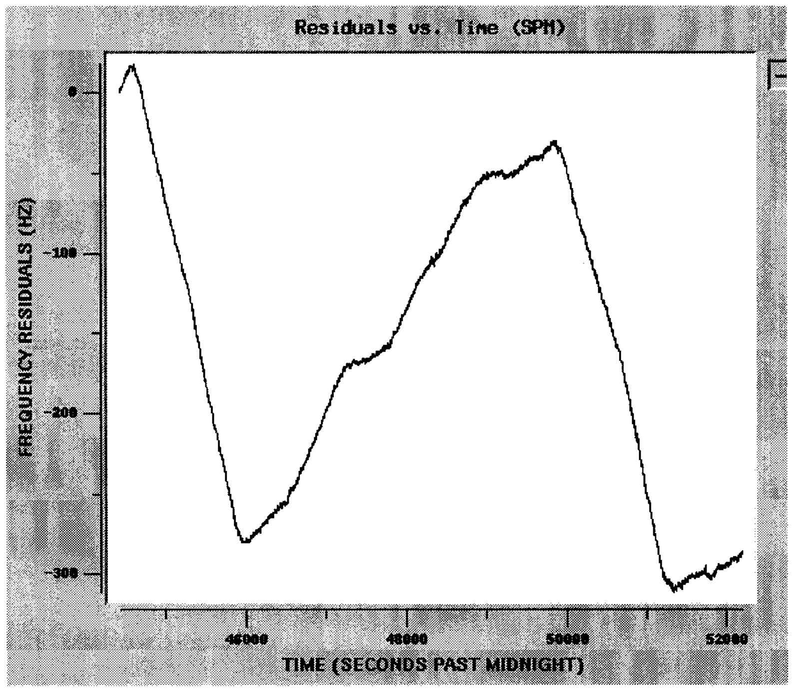


Allan Deviation of X-Ka Band Residuals

Flight Validation Results - NonCohernet Downlink

- Noncoherent (AusOsc) downlink is sensitive to temperature variation (approx. 800 Hz/C at X-band and 3.2 kHz/C at Ka-band)
- Measured frequency variation is highly correlated between X- and Ka-band as expected. The contribution may be due to less than 0.1C change in temperature





SDST Ka-band Validation Results

- Demonstrated SDST capability to support simultaneous X and Ka-band downlinks at various data rates and modulation indices
- Verify X/Ka band Radio metrics performance
  - Measured one-way and two-way frequency stability and X-Ka-band relative frequency stability
  - Demonstrated X and Ka-band ranging capability
- Demonstrated operation of 3W (2.5W) Ka-band SSPA in space
- Collected operating data for the Ka-band SSPA (gate current and drain voltage telemetries and operating temperature data) for future analysis
- Demonstrated DSN readiness to support Ka-band mission
  - Demonstrated dual-band (X/Ka) end-to-end telemetry flow from spacecraft to DS1-MSA
  - Demonstrated capability to generate necessary station predicts for Ka-band
  - Demonstrated station capability to perform radio metric tracking on Ka-band downlink (Doppler and ranging)
  - Demonstrated DSS-25 capability to accurately point the 34 m antenna using blind pointing
- Measured Ka-band system noise temperature and telemetry detection threshold

Summary and Conclusions

- **Key functions of the SDST have been fully validated in space**
  - **Successful flight validation significantly reduces risk for future missions to employ the SDST**
- **Development for Mars 01/SIRTF has resulted in further improvements in SDST functionalities**
  - **Corrected problem with changing receiver best lock frequency**
  - **Corrected nonlinearity of phase modulator**
  - **Corrected large subcarrier frequency shift over temperature**
  - **Allow for dual string CDS cross strapping with the transponder**
- **SDST is ready for flight!**